Resorting the NIST Undulator using Simulated Annealing for Field Error Reduction

Greg Denbeaux[1], Lewis E. Johnson[2], John M.J. Madey[3]

[1]*Duke Free Electron Laser Lab, Department of Physics, Duke University, Durham, NC 27708*
[2]*Center for X-ray Optics, Lawrence Berkeley National Lab, Berkeley CA 94720*
[3]*Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822*

Abstract. We have used a simulated annealing algorithm to sort the samarium cobalt blocks and vanadium permendur poles in the hybrid NIST undulator to optimize the spectrum of the emitted light. While simulated annealing has proven highly effective in sorting of the SmCo blocks in pure REC undulators[1-5], the reliance on magnetically "soft" poles operating near saturation to concentrate the flux in hybrid undulators introduces a pair of additional variables – the permeability and saturation induction of the poles – which limit the utility of the assumption of superposition on which most simulated annealing codes rely. Detailed magnetic measurements clearly demonstrated the failure of the superposition principle due to random variations in the permeability in the "unsorted" NIST undulator. To deal with the issue, we measured both the magnetization of the REC blocks and the permeability of the NIST's integrated vanadium permendur poles, and implemented a sorting criteria which minimized the pole-to-pole variations in permeability to satisfy the criteria for realization of superposition on a nearest-neighbor basis. Though still imperfect, the computed spectrum of the radiation from the re-sorted and annealed NIST undulator is significantly superior to that of the original, unsorted device.

Introduction

The NIST Undulator is a hybrid undulator composed of Sm_2Co_{17} permanent magnets paired with vanadium permendur pole pieces that has been installed on the Duke 1GeV Storage Ring[6]. The NIST undulator has 130 periods each 2.8cm long and a total of 520 magnet and pole pairs. When it arrived at Duke University a few years ago, the magnetic field errors on the axis of the undulator were quite large which would have lead to a poor spectrum of light from the undulator. We worked on correcting the field errors with the primary goal of optimizing the spectrum. We employed a variety of techniques including applying a simulated annealing algorithm to sort the magnet and pole pairs into an optimal order.

To implement the annealing algorithm, we first determined what effect different magnet and pole pairs had upon the field on axis. We found that to optimally improve the spectrum of light from the undulator, the simulated annealing algorithm must take into account both the magnetic field strength of the magnets and the permeability of the pole pieces.

The simulated annealing algorithm works by simulating the switch of two magnets/pole pieces with known characteristics and calculating the change that this switch has on the overall field down the undulator. In order to reduce the chance of sorting the system in to a local rather than global minima, the sorting algorithm starts in a more random or high "temperature" state. When this "temperature" is high, the sorting algorithm may swap two magnets even if it does not decrease the overall field errors. Then, this "temperature" is slowly reduced, and magnets finally only switch positions when it reduces the field errors. With this procedure, the chance of reaching global minima in overall undulator field errors is increased.

Experimental Measurements

In order for the simulated annealing algorithm to be successful, the change in the field caused by switching two magnet/pole pieces must be known. This has been shown to work for pure permanent magnet undulators [1-5]. We found that for a hybrid undulator, the differences in the characteristics of the individual pole pieces was an important criterion for the simulated annealing sort. For magnet/pole pieces which had similar pole pieces and magnets that differed in strength, by 1%, the change in the magnetic field above that pole and nearby poles closely matched the Mermaid[tm] magnetic simulation program and is shown by the solid line in Figure 1. The surprising result is the dotted line in Figure 1 which is the change in field caused by switching one magnet/pole piece which also has a 1% difference in magnetic field strength of the magnet, but also has different permeability and saturation characteristics of the pole piece. This clearly does not cause the same change and must be taken into account before performing a simulated annealing sort.

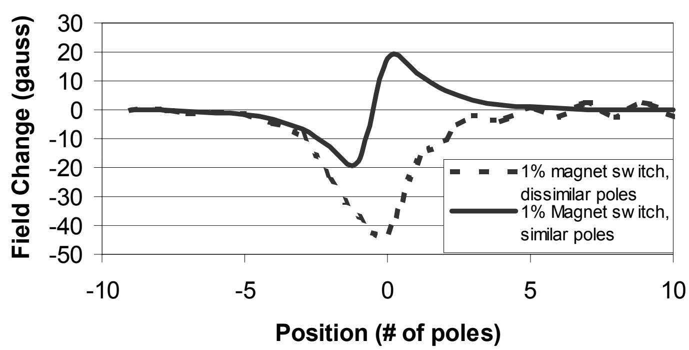

FIGURE 1. Field change due to swap of magnet/ pole pair with 1% different field strength and similar pole pieces and swap of magnet/pole pair with 1% different field strength and dissimilar pole pieces.

We measured each magnet/pole pair (which was permanently attached together as one unit) two different ways. First we measured the magnet strengths by using a hall probe above the face of the pole while each pole and magnet pair was held in free space. In this situation, the fields were low enough that the different saturation effects of the poles did not affect the field measurements. The fields varied by over 4% from the mean field at 1603 gauss. Then we measured the field strength of each pole and magnet pair in a situation which more closely simulated the fields present while installed on the undulator. For this configuration, each magnet/pole pair was mounted on an L shaped iron yoke with the magnet side of the magnet/pole pair against the L shaped yoke. There was a small air gap of approximately 7mm between the pole tip and the other side of the L shaped yoke. This gap was chosen so the field above the pole tip nearly matched the fields present while installed on the undulator. The field in this gap was measured with a hall probe.

Pole Saturation Effects

With these two measurements, we can distinguish between poles that have different saturation characteristics. If we apply Ampère's law to a closed loop with constant B through the steel yoke, the magnet, the pole, and the air gap, we get:

$$\oint H \cdot ds = 0, \tag{1}$$

with

$$H = \frac{B}{\mu} - m. \tag{2}$$

In the iron yoke, $s=s_1$, $\mu=\mu_1$, $m=0$. In the samarium cobalt magnet, $s=s_2$, $\mu=\mu_2$, $m=M$. In the vanadium permendur pole, $s=s_3$, $\mu=\mu_3$, $m=0$. In the air gap, $s=s_4$, $\mu=1$, $m=0$.

Then, solving for M/B yields:

$$B = \frac{s_2 \cdot M}{\frac{s_1}{\mu_1} + \frac{s_2}{\mu_2} + \frac{s_3}{\mu_3} + s_4}. \tag{3}$$

$$\frac{M}{B} = C_1 + \frac{C_2}{\mu_3}, \tag{5}$$

Where C_1 and C_2 are constants. The measurement of magnet strength in free space is proportional to the magnetization of the SmCo magnet, M. The measurement of the magnetic field in the air gap while mounted on the iron yoke is proportional to B. The ratio of M/B gives μ_3, within a scale factor for each pole. With the measurement of μ_3 for each pole, we modified the sorting algorithm to require that the nearest neighbor poles must have similar saturation characteristics

After modification of the simulated annealing algorithm and other magnetic field corrections, there was remarkable improvement in the expected spectrum from the device[6]. Calculations of the spectrum based on measured magnetic field errors predicted that the third harmonic would improve from 50% of the theoretical maximum to 90% of the theoretical maximum. The spectral intensity of the first harmonic would also increase to about 90% of the theoretical maximum.

Conclusions

The compensation of hybrid undulators to the exacting specifications required for the generation of UV and x-ray undulator and FEL radiation requires attention to the pole to pole variations in permeability and saturation as well as the magnetization of the rare earth-cobalt (REC) or neodymium-iron blocks generating the field.

While simulated annealing has been used with great effectiveness in the compensation of pure REC undulators in which the permeability can, with adequate accuracy be assumed equal to unity, pole-to-pole variations in the permeability and saturation of the soft iron plates used to collect and shape the field in hybrid undulators can invalidate the assumption of superposition on which the sorting algorithms for the classic simulated annealing algorithms depend.

By resorting the REC blocks and attached soft-iron poles of the Duke/NIST undulator with the constraint that near neighbors pole pieces had similar permeability and adding a coil to compensate for the overall dipole error in the field of the assembled undulator, it was possible to achieve a field configuration which yielded near-optimal brightness at both the fundamental emission wavelength and at the low order harmonics under the standard operating conditions for the Duke 1 GeV ring.

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